Remote Sensing Applications of a Free-electron Laser Lidar

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Abstract—This paper a high average power and high spectral brightness free-electron laser (FEL) being developed at the University of Hawaii as a lidar transmitter for atmospheric and oceanic research. The FEL will be tunable from the UV to the mid- infrared. Peak power in the picosecond long micropulses of the FEL will reach 10s of MW, and these will average to the order of 100 kW over the 5 microsecond long macropulses. The repetition rate of the micropulses will be in the range 1 to 3 GHz during one macropulse, and the macropulses will repeat at 180 Hz. The unique pulse structure of the FEL output with high pulse power will allow exploitation of non-linear optical spectroscopic techniques for identifying various types of aerosols and pollutants in the atmosphere. The wide tunable range in the mid-IR region will allow sensitive detection of chemical species by operating the FEL transmitter in the differential absorption lidar (DIAL) mode, and the high spectral brightness will allow unprecedented signal-to-noise ratio.

1. INTRODUCTION

Advances in the fields of active remote sensing and pollution monitoring with lidars are usually related to progress in tunable high power laser sources. Inherent wavelength tunability of the FEL (UV to mid-IR) and its ability to produce substantial output power make it possible to realize a powerful remote sensing system for atmospheric and marine research. Advantages of using a tunable FEL for detection and ranging (FELDAR) of the atmosphere and ocean have been discussed by a number of researchers [1-4]. However, most FELs operated to date have in essence been constructed as laboratory prototypes. These laboratory FELs are designed without regard to the need to transport the laser hardware to remote sites where it will be used. Very little attention has been paid to operation of FEL hardware in the field without the massive power, utility, and shielding systems incorporated as a part of infrastructure in fixed laser laboratories. There is a need to develop a FEL that can be transported to the site of operation in standardized containers with the rest of the hardware required for lidar operation.

In this paper, we describe in brief a high average power and high spectral brightness free-electron laser being developed at the University of Hawaii as a lidar transmitter for field deployment at the Pacific Missile Range on the Island of Kauai for remote sensing applications.

2. FEL INSTRUMENTATION

The FEL that will be used as a lidar transmitter is a direct descendant of the workhorse Mk III FEL [5], incorporating innovations demonstrated with the Mk III during the university-industry collaboration of FEL groups headed by one of the authors (JM) during the late 1980s. Among the most important of these innovations were the UV-driven photoinjector [6] and operation of two FELs with a single linear accelerator [7]. Subsequently the Rocketdyne Division of the Rockwell International Corporation further developed the photoinjector, a 5-meter linac using SLAC linac sections modified for higher peak and average currents, a new RF system based on the 65-MW peak-power SLAC 5045 klystron, and a second 2-meter wiggler [8]. This FEL hardware, which has been donated to the University of Hawaii, will be augmented with features stressing agile wavelength tuning over the necessary wide range needed for a hyperspectral lidar transmitter as well as linewidth narrowing capability. The projected performance of this system (the Mk IV FEL) is summarized in Table 1.

The laser output mimics the temporal structure of the electron beam lasing medium, producing picosecond pulses that have had relatively large linewidth in the past (6 - 40 cm^{-1}). However, interferometric [9] and injection seeding [10] techniques have been successfully applied in recent years to spectrally narrow FEL output (210 MHz; 0.003 cm^{-1} at 3 µm). In a recent development, operation with phase-locked pulses has demonstrated a 100-MHz linewidth, and an intracavity Fox-Smith interferometer is being developed to achieve single mode (sub-MHz linewidth) output appropriate for Doppler-free spectroscopy, with single-mode power up to 250 W..

Broad Wavelength Tunability

Tunability in the IR provides access to the rich spectroscopy of transitions between vibrational and rotational energy levels in molecular species, but additional important remote sensing objectives depend on shorter wavelengths. For example wavelengths from For the mid-IR down into the visible range are needed for aerosol backscatter and size distribution measurements [11]. Hyperspectral lidar can serve as a tool to monitor atmospheric effects as disparate as volcanic dust and sea salt and other agents of nucleation that

Table 1. The Mk IV FEL Parameters

• Wavelength tuning range	200 nm to 10 µm
• Wavelength switching rate	up to 1.5 GHz
• Spectral purity	6 to 40 cm^{-1} for free-running psec pulses < 1 MHz for phase-locked psec pulses
• Micropulse repetition rate	up to 3 GHz (thermionic injector) up to 95 MHz (photocathode injector)
• Macropulse repetition rate	1 to 180 pulses per sec (pps)
• Micropulse duration	0.5 to 5 psec
• Micropulse peak optical power	up to 50 MW (thermionic injector)* up to 350 MW (photocathode injector)
• Macropulse duration	up to 5 µsec*
• Macropulse optical power	up to 100kW*
• Average optical power	up to 200 W at 180 Hz*

* Some parameters are asterisked to emphasize optical wavelength dependence of performance

strongly influence the meteorology, for example, in the coastal theatre. Visible wavelengths also interact strongly with the metallic layers in the mesosphere, providing, for instance, an important probe of the upper atmosphere to check global circulation models [12]. Fluorescence induced by blue-green laser radiation, for instance, will allow observation of marine organisms [13]. UV wavelengths have been used to observe chromophoric dissolved organic carbon (c-DOC) in the oceans [14]. Tuning to the blue-green portion of the visible spectrum will give optimum transmission in seawater, of use for underwater imaging.

The Mk IV FEL will also provide an opportunity to field test and utilize techniques for ultra-sensitive absorption spectroscopy. Recently, very high detection sensitivity for CH_4 has been demonstrated using, the GHz-rate pulse train from a phase-locked FEL, in which the fractional power absorbed from one or more laser lines reappears as a signal on the dark background between the pulses emerging from the sample. Specifically absorption experiments in 15 Torr cm of methane at 3.25 µm, using phase-locked pulses from the Mark III FEL, have clearly reveal an interpulse beat signal due to absorption by adjacent molecular rotational lines which is generated only in the presence of interpulse phase coherence. [15]. The FEL modulation spectroscopy technique for real-time applications of trace-gas analysis, in remote sensing seems very promising.

Wavelength Agility

The ability to change wavelengths on short time scales is fundamental to the effective conduct of the Mk IV FEL's intended mission, envisioned as supporting a complex program of optical observations with a number of experiments in the field at any one time. Differential absorption lidar (DIAL) requires illuminating the target with light at two discrete wavelengths narrowly separated both spectrally and temporally. Some individual studies will require scanning wavelengths, e.g., obtaining the size distribution of aerosols or the concentrations of multiple species in urban and volcanic pollution episodes. DoD applications will have similar needs, including atmospheric and oceanographic research, but also demonstrations of long range detection of missile plumes or chemical and biological weapons; high wavelength agility would be a key feature in demonstrations of defense applications such as optical countermeasures.

An innovation in the Mk IV FEL will achieve very rapid wavelength changes solely by adjusting the electron energy, $(_e$, according to the familiar relationship:

$$l = \frac{l_{\text{wiggler}}}{2g_e^2} \times \left[1+a_w^2\right] \qquad (1)$$

Where $\lambda_{(wiggler))}$ is the magnetic field wiggler periodicity, $(_e$ is the relativistic energy of electrons, and $[1+a_w^2]$ is a function that determines the dependence of FEL wavelength on the magnetic field of the wiggler. FEL tuning is typically accomplished by varying the field strength of the wiggler magnet ($a_w{}^2$), but the mechanical motions involved render this tuning method inherently slow. Alternatively the electron energy can be changed rapidly, but in existing FEL configurations there is a concomitant need to simultaneously change the settings of beamline magnets. This is limited to kHz rates at best and is a potential source of performance-degrading electron beam emittance growth.

The innovative approach to tuning via the electron energy in the Mk IV will involve inserting a short section of accelerator inside the optical resonator, just upstream of the wiggler [3]. A need to reset magnets to accommodate these energy changes is therefore avoided. Providing $\delta(_e$ of energy to the electron beam, this auxiliary accelerator can be used to change wavelength from one macropulse to the next at 180 Hz. With the auxiliary accelerator excited at one-half the frequency of the main accelerator the wavelength can be switched from one micropulse to the next, resulting in the ability to switch wavelengths at rates up to 1.5 GHz.

3. CONCLUSIONS

The unique pulse structure of the Mk IV FEL output combined with its high pulse power will allow exploitation of non-linear optical spectroscopic techniques (e.g., two photon fluorescence, Raman, etc.) for identifying various types of aerosols and pollutants in the atmosphere. The wide tunable range in the mid-IR region will allow sensitive detection of chemical species by operating the FEL transmitter in the differential absorption lidar (DIAL) mode, and the spectral brightness will allow unprecedented signal-to-noise ratio.

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